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EXECUTIVE SUMMARY

DEFECT DEPTH MEASUREMENT INPRESSURE TUBES USING ULTRASONIC CRACK-TIP DIFFRACTION

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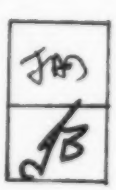
Currently there is no reliable method of measuring defect depths in CANDU reactor pressure tubes. The demonstrated success of crack-tip diffraction (or time-of-flight-testing) in round-robins on thick components has promoted an interest in this technique. In CANDU reactors, pressure tubes are effectively accessible only from the inside. Development work has concentrated on outside surface defects using 45 degree shear waves in contrast to the longitudinal waves usually used for testing thick components with this technique. Due to the small wall thickness of the pressure tubes (4.2 mm) and the typical sizes of defects of interest (0.15 mm or greater), frequencies of the order of 20 MHz are being used. A further complication comes from the orientation of the defects, which may be at any angle in pressure tubes.

Initial studies have been performed on a series of outside surface notches and slots, plus a real fatigue crack. This crack was on the inside surface, so the technique required measuring this defect's depth from the outside. Initial results are encouraging. Even without signal processing, crack-tip diffracted signals were detectable from all but very large (2.5 mm) and very small (less than 0.076 mm) notches. Errors in estimates of defect depths were typically less than 0.1 mm for all the notches, and the results were consistent. Measurements on the fatigue crack showed similar random errors, though there appeared to be a deterministic error of about 0.1 mm as well.



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TO: Mr. D. M. Hayter
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H15A11

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Currently there is no reliable technique for measuring defect depths in pressure tubes. Ultrasonic crack-tip diffraction, which measures the time-of-flight of weak re-radiated waves from the tips of defects, has shown good accuracy in larger components. This report briefly describes the principles of crack-tip diffraction, its initial adaption to pressure tubes, and some early depth measurements on OD notches, slots and a real fatigue crack.

1.0 INTRODUCTION

1.1 The Need for Defect Depth Measurements

Nuclear power is suffering from a number of problems, which include safety considerations, nuclear waste, regulatory hurdles (particularly in the U.S.A.), costs and materials failures. While materials failures are relatively uncommon (relative to, say, thermal power), their impact tends to be disproportionately large. The recent hydride blistering at Pickering 1 and 2 is a good example/1/, where one tube failure caused the shutdown of two reactors for a number of years, at enormous cost.

In the last few decades, there has been considerable progress in technical areas such as fracture mechanics and stress analysis, which has allowed materials to be more economically used. It has also allowed operation of components which contain defects, whereas previously such defects or components would automatically have been removed. However, defects left in during operation typically require the use of some monitoring or nondestructive evaluation (NDE) technique.

1.2 Crack-Tip Diffraction

Ultrasonics is one of the prime methods of inspecting and monitoring components for defects. Ultrasonic inspections can be broadly classified into three stages: detection, characterization and sizing. The recent PISC II round-robin test program showed that defect detection on large ferritic steel components is quite good. However, the sizing of these defects showed large variations/2/. Furthermore, from a fracture mechanics view-point the important parameter is defect depth (rather than defect length), which is also the hardest parameter to measure. Current ultrasonic practice performs defect depth measurements by a technique such as 6 dB drop-off, but this uses signal amplitude which depends on several defect-related variables. A number of other ultrasonic approaches, such as defect shadowing or absolute signal amplitude have been tried, as well as other techniques such as eddy current. All these defect depth measurement techniques have defect-related limitations.

More recently, an ultrasonic technique called "crack-tip diffraction" (CTD) or "time-of-flight diffraction" (TOFD) has been developed commercially by the UKAEA Harwell. CTD uses a wave physics-type approach for defect sizing. The major advantage of this approach is that it does not rely on received signal amplitude for the actual measurement of defect depths: CTD uses time-of-flight measurements, which can be extremely accurate. The major disadvantage of the technique is that crack-tip diffracted signals are very weak. This report describes the initial modification of the CTD technique to CANDU reactor zirconium-niobium pressure tubes, and preliminary results on outside surface notches of various dimensions plus a fatigue crack.

2.0 CRACK-TIP DIFFRACTION

2.1 Background to CTD

When an ultrasonic wave strikes a crack within a solid, the energy can go through a number of processes: reflection, absorbtion, transmission, mode convertion, or diffraction. The interaction of the ultrasound beam with a defect is extremely complex, and considerable resources have been spent trying to analyse it. For example, the USAF/DARPA have funded several workers trying to deconvolve the ultrasonic spectrum to develop a technique for predicting defect size and shape, with little apparent success/3/. In contrast, several British workers (see section 2.2 below) have used geometric diffraction theory to develop comprehensive wave physics models which are now in general use. The complexity of the crack/beam interaction depends not only on the incident wave, but also heavily on the defect itself.

Besides reflection and transmission, the defect absorbs some of the energy of the incident ultrasound beam. Some of this absorbed energy is re-radiated from the tips of the crack, much like the ringing of a tuning fork. These crack tip signals tend to be re-radiated in all directions though with different signal amplitudes, ie, the tip behaves as a secondary point source. These waves can be detected, as with other ultrasound waves, though they are typically very weak (low signal amplitude) relative to reflected waves. Since the tip-diffracted

waves come from a point source, they have a very precise time of arrival, and hence can be used as a method of measuring crack depth using simple trigonometry. Figure 1 shows a schematic of the generation of diffracted and reflected waves at a crack, plus typical wave paths from the transducer to receiver probes. Figure 2 shows the screen pattern from diffracted and reflected waves.

The intensity of the diffracted wave is very dependant on incident angle in particular, as well as wave mode and various other features (such as the orientation of the defect itself). By choosing favourable angles and modes, the signal strength can be optimized. It may also be improved by signal processing such as signal averaging. Typically the diffracted wave time-of-flight is measured relative to a reference signal, such as the lateral wave or backwall, depending on the component configuration.

2.2 Research Work on CTD

Most of the early work on the application of CTD was performed by the UKAEA Harwell, initially by Silk/4/. Harwell has developed a data processing system called Zipscan/5/, which can perform CTD using contact ultrasonics on thick components. Zipscan collects data, performs box-car signal averaging, corrects the resultant B-scan image to compensate for defect position in the component, then performs synthetic aperture focussing to improve the picture. The result is a readily readable image which can even indicate the top and bottom of defects by phase. CTD demonstrated itself highly successfully on the British Defect Detection Trials, where the results were accurately generated and analysed in a very short period of time/6/. (However, even Harwell do not recommend the use of CTD in isolation due to the low amplitude signals).

The CTD/TOFD approach has stemmed from wave physics work performed by workers in the UK at Harwell, as well as others like Coffey et al in the CEGB/7/ and Bond at Imperial College/8/. Further CTD/TOFD studies have been performed by US workers such as Achenbach et al/9/, Adler et al/10/ and Tittman/11/. Almost without exception, this work has concentrated on thick, simple geometries. Zipscan uses low frequency (about 2 MHz) unfocussed probes, primarily in contact mode, for looking at large defects in very thick plate (250 mm) for reactor pressure vessels. There has been very little work done on thin components, such as pressure tubes.

2.3 Adaption of CTD to CANDU Pressure Tubes

For thick section components, the ultrasonic wavelength is small (c. 2 mm) compared with defect size (c. 15 mm). For pressure tubes, much shorter wavelengths are required since this parameter ultimately limits the resolution of the system. The defect dimensions of interest range from less than 0.15 mm (0.006") to about 2.5 mm (0.1"). Unfortunately, this also indicates that the wavelength and defect may be of similar size, which may complicate the wave physics. Thus, for CANDU pressure tubes, selection of frequency may be very important. Zipscan uses a very wide beam for large defects, while pressure tube inspections are primarily interested in rather small defects. This suggests focussed transducers may be better for CANDU.

While primarily a data collection system, when used with CTD Zipscan aims at measuring vertical defect depths, and typically uses 45 degree longitudinal waves. In contrast, experience with defects in pressure tubes has shown that they can be either vertical such as delayed hydride cracks, multi-oriented such as hydride blisters, or severely angled such as manufacturing defects. In pressure tubes, defects can be classified as either inside surface or outside surface. In practice, outside surface defects are likely to be easier to measure using CTD, so the initial investigations have started with these. Reflections from inside surface defects are likely to become confused with the front wall signal.

3.0 EXPERIMENTAL

3.1 Equipment

Four small, highly damped ultrasonic probes were purchased, two nominally 15 MHz and two 20 MHz. The dimensions, theoretical near field, experimental near field, wavelength and beam spread angle are given in Table 1. All the probes were unfocussed. A variety of ultrasonic equipment was used, including a Krautkramer KB6000 ultrasonic flaw detector, a Panametrics 5600 Ultrasonic Analyzer, a Tektronics 7854 Digital oscilloscope and a Hewlett-Packard 8352-3 Spectrum Analyzer. The probes were beam profiled, and the shape and the frequency spectrum of the pulses recorded (see Figure 3 for an example).

The ultrasonic probes were mounted on a single skip inspection module compatible with a CIGAR head. The CTD module had three probe locations: two for 45 shear wave, circumferential-facing CIGAR-size probes, and one for a small central normal beam probe (see Figure 4). The position of the probes was chosen so that the three beams all met at the same point on the outside surface of the pressure tube.

Three different methods were investigated for measuring crack depths, though only one geometric approach (using symmetric probe positions) was used in the final analysis. The geometry and calculations used are shown in Figure 5. Note that this approach uses an approximation strictly valid only for shallow defects. This relationship is similar to those used elsewhere/10/ for thick components.

3.2 Manufacture of Notches, Slots and Hubert's Crack

Outside surface axial EDM notches were made in a long section of pressure tube, nominally 0.076, 0.15, 0.25, 0.635 and 1.27 mm deep and 6.35 mm long (see Table 2 and Figure 5). For measuring notch depths, the CTD module was attached to a CIGAR head to ensure repeatable centering.

Outside surface axial machined grooves were also made in a short piece of Zr-Nb pressure tube at nominal depths of 0.15, 0.25, 0.635, 1.27, 2.03 and 2.54 mm (see Table 3 and Figure 6). For measuring groove depths, a special holder was made to centrally mount the CTD module and rotate it by hand.

Hubert's crack is the nickname given to an inside surface fatigue crack manufactured by a University of Toronto student/12/. The crack was grown in a piece of ZrII pressure tube, and the starter notch machined off. Thus the Hubert's crack pressure tube is somewhat oversized, and did not readily fit the CTD jigging. Consequently Hubert's crack was measured from the outside of the pressure tube, using a lash-up jigging system and adjustable probe angles rather than the CTD module. This set-up tended to be difficult to reproduce reliably (Figure 7). Hubert's crack has been carefully measured using normal beam ultrasonics, and the results correlated with fracture mechanics predictions.

All the actual depth measurements were performed using the Panametrics pulser and Tektronix oscilloscope. Time-of-flight differences were measured using stored digital waveforms on the oscilloscope, and multiple waveforms could be displayed for convenience in analysing signals. For reporting purposes, waveforms were photographed from the screen, either singly or overlaid. Typically, measurements were made from the top of the first peak of the signal, though the optimum location for measurements requires further investigation.

4.0 RESULTS

Table 2 shows the predicted and measured depths of the EDM notches. The 0.076 mm notch was not detectable or measurable since the crack-tip diffracted signal was lost in the backwall signal. However, the 0.15 mm notch was more readily measurable, as shown in Figure 8. The 0.25 mm notch was clearly visible (see Figure 9). In most cases, the errors are under 0.03 mm, indicating a high degree of accuracy with this technique. Given the approximation in the calculation described earlier, it is not surprising that errors are greatest on the deepest notch. (Note that the correlations assumed the notches were exactly the stated depths. Previous work using replica material has shown that actual depths are usually within 0.025 mm of the nominal depths, though later it may be advisable to confirm these notch depths.)

Table 3 shows the nominal and measured machined slot depths with errors. As with the EDM notches, the errors are small. In this case, the errors tended to be greatest in the smallest and largest notches, which is no surprise since the signals are hardest to distinguish in the first case, and the probes are set-up for small outside surface notches in the second case. Furthermore, the slots were machined with a triangular cross-section, which probably makes them even less representative of actual defects than EDM notches. Note again that slot depths are nominal. Figures 10-13 show sample overlaid signals from the 0.15, 0.25, 0.635 and 1.27 mm slots.

Table 4 shows predicted/13/ and measured depths of Hubert's crack at various locations up and down the tube. The difference between the two shows a fairly consistent error of about 0.1 mm, plus an apparent random component. Given the relatively poor jigging used for Hubert's crack, a consistent error is not surprising. Despite this, the correlation between predicted and measured values is good. It should also be appreciated that CTD will tend to integrate over a length of at least 1 mm due to the beam width. Figures 14-20 show a series of oscilloscope traces with the CTD signal and backwall.

5.0 DISCUSSION

The initial measurements using CTD on EDM notches, slots and Hubert's crack in pressure tubes show encouraging results for measuring crack depths. Errors are small, and with the exception of very small (0.076) and large (2 mm plus) defects, appear to be consistent. This strongly indicates that a reliable technique for crack depth measurement can be developed for in-reactor use. At this stage there does not appear to be any major technological barrier to the use of CTD for outside surface defects with CIGAR. However, CTD signal amplitudes are very low, and there are typically many signals possible from any given defect, so considerable effort can be anticipated before a reliable technique is developed.

There are a number of problems or development stages to be overcome. First, the technique will need to be demonstrated on real cracks which will later need to be sectioned for confirmation. Conveniently, the Fracture Mechanics Unit is manufacturing part-through cracks in pressure tubes, so this step should occur shortly. Second, the ultrasonics will need to be optimized in terms of probe size, frequency, pulse shape and damping. A PC-based pulser board with pulse shaping capabilities is on order, and more ultrasonic probes have been purchased. Third, the pulser and receiver probe angles require more investigation, both for radially oriented defects and for highly "misoriented" ones. A variable angle jig is currently being designed. Lastly, the technique will need adapting for inside surface defects, which may require advanced signal processing to extract small signals from within larger ones.

6.0 CONCLUSIONS

1.0 Crack-tip diffraction on notches, slots and a fatigue crack in Zr-Nb pressure tubes has shown that the technique has the potential of consistently measuring defect depths to within 0.1 mm.

2.0 Further developments in jigging, ultrasonic probes and pulse shaping should improve the reliability and accuracy of CTD for outside surface defects.

7.0 RECOMMENDATION

Work on CTD should continue, with emphasis on incident and reflected beam angles, probes and pulse shaping. Initially, tests should be concentrated on outside surface defects, and on real fatigue cracks.

8.0 ACKNOWLEDGEMENTS

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TABLE 1

Physical Parameters of Ultrasonic Probes Used

Probe	Dimension (Diameter) mm	Nominal Freq. (MHz)	N (mm)	N' (mm)	λ (mm)	γ (deg)
Harisonic I21502G s/n A10280	3.175	15	25.2	21.1	0.16	3.5
Harisonic I21502G s/n A10288	3.175	15	25.2	18.0	0.16	3.5
Harisonic I22002G s/n A10289	3.175	20	33.6	17.2	0.12	2.6
Harisonic I2200G s/n A10291	3.175	20	33.6	19.6	0.12	2.6

Where: $N = D^2/4\lambda$ theoretical Near Zone
N' = Near Zone measured from the beam profile
λ = Wavelength
D = Probe diameter
γ = Beam spread ($\gamma = 1.2\lambda/D$)

Note: All the probes were unfocussed.

TABLE 2

Measured Depths of EDM Notches

Depth to Tip mm (Thou)	Travel Time Difference (μsec)	Predicted Depth (mm)	Nominal Error (mm)	Comment
0.0762 (3)	-	-	-	no signal detected
0.1524 (6)	0.075	0.13	-0.0224	
0.254 (10)	0.15	0.2598	0.0058	
0.635 (25)	0.35	0.606	-0.029	
1.27 (50)	0.8	1.38	0.11	

Note: The notches were assumed to be obtained exactly at the stated depth. The signal from the 0.0762 mm notch-tip was too close to the backwall to be separated.

TABLE 3

Measured Depths of Slots

Depths to Tip mm (Thou)	Travel Time Differences (μsec)	Predicted Depth (mm)	Nominal Error (mm)	Comment
0.1524 (6)	0.05	0.086	-0.0664	
0.254 (10)	0.15	0.2598	0.0058	
0.635 (25)	0.35	0.606	-0.029	
1.27 (50)	0.78	1.35	0.08	
2.032 (80)	1.21	2.09	0.058	
2.54 (100)	-	-	-	no signal detected

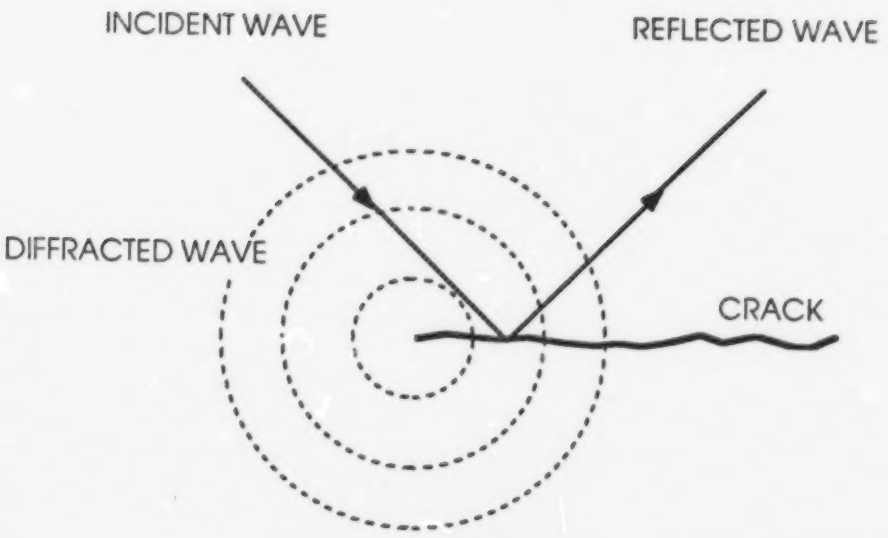
Note: The slots were assumed to be machined exactly to the stated depth. No signal was detected from the 2.54 mm slot: its depth is over half way through the tube wall, and the probes are focussed near the outside surface.

TABLE 4

Measured Depths of Hubert's Crack at Selected Locations

Axial Distance (mm)	Travel Time (μsec)	Predicted Depth (mm)	Measured Depth (mm)	Difference (mm)
7.5	0.250*	0.433	0.580	0.147
10.5	0.281	0.487	0.632	0.145
13.5	0.352	0.609	0.668	0.059
16.5	0.383	0.663	0.763	0.100
24.5	0.312*	0.541	0.654	0.113

Note: The axial distance is measured from the bottom of the tube; measured depth according to Reference /10/. Signals marked with * were barely visible.



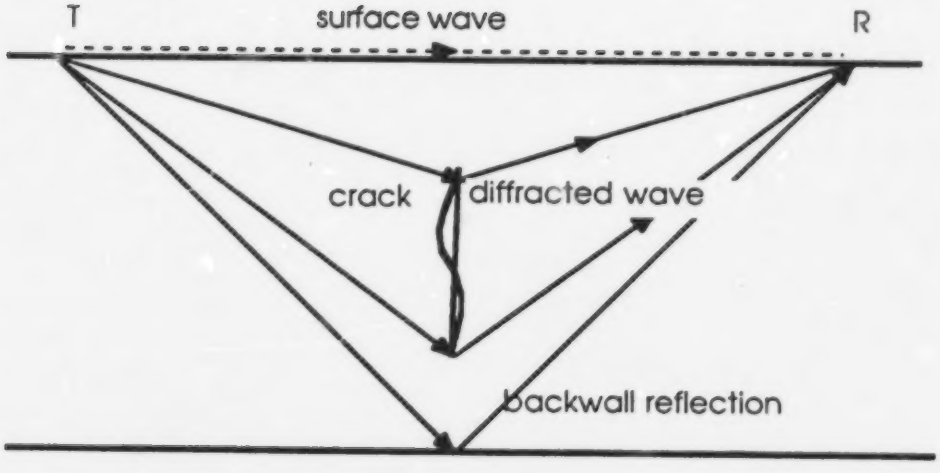


FIG. 1

SCHEMATIC DIAGRAM OF THE INTERACTION OF AN ULTRASONIC WAVE WITH A DEFECT, AND PRESUMED PATHS TAKEN BY THE SIGNALS IN THE DIFFRACTION TECHNIQUE

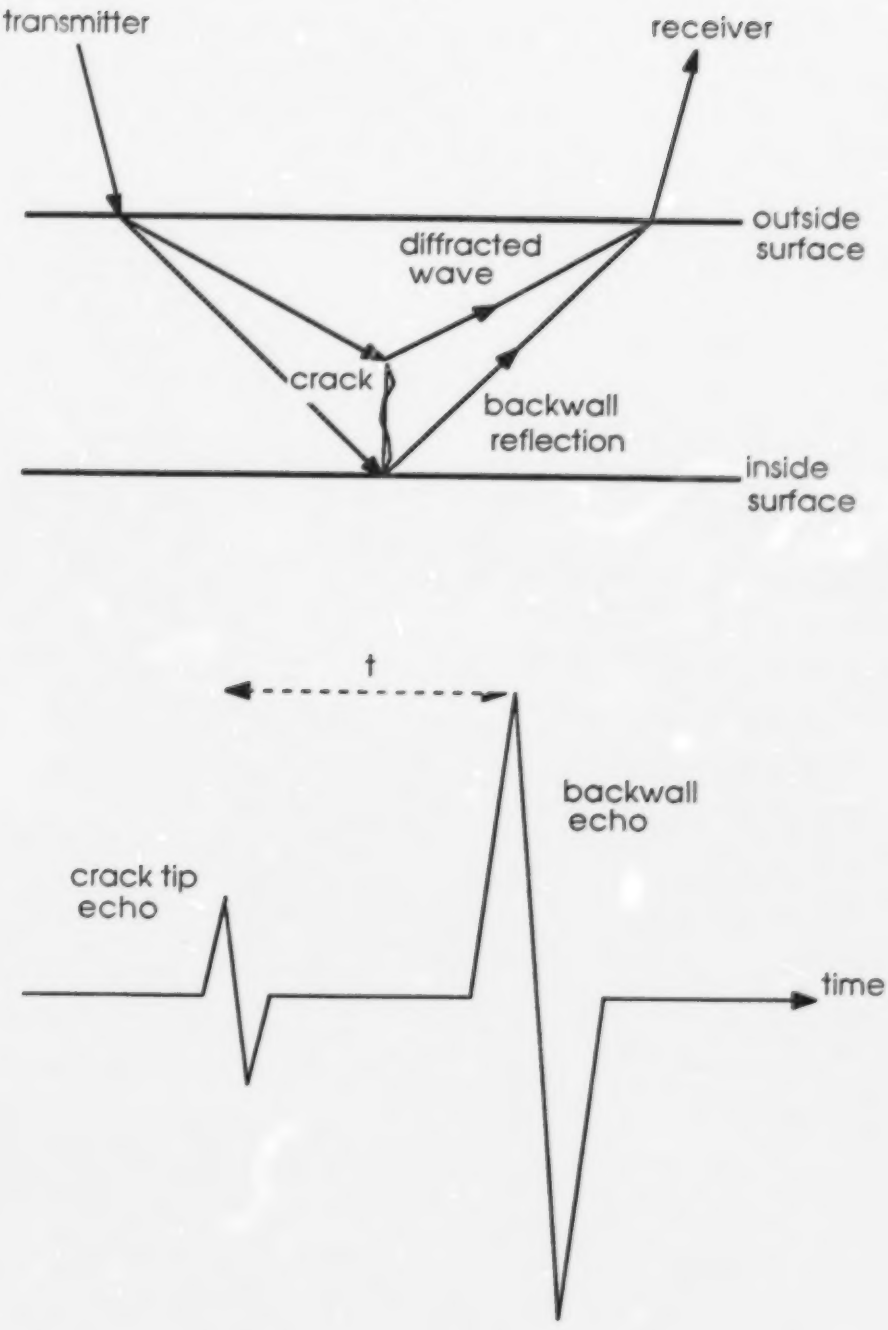
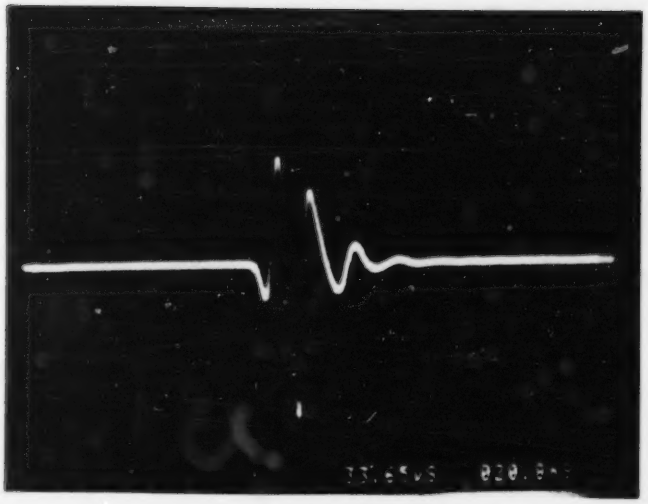


FIG. 2
DIFFRACTED AND REFLECTED WAVES
AND SCREEN PATTERN

172622-RD



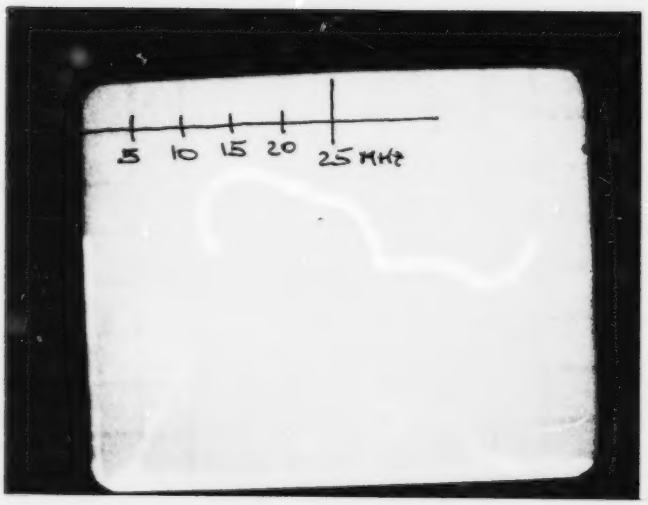
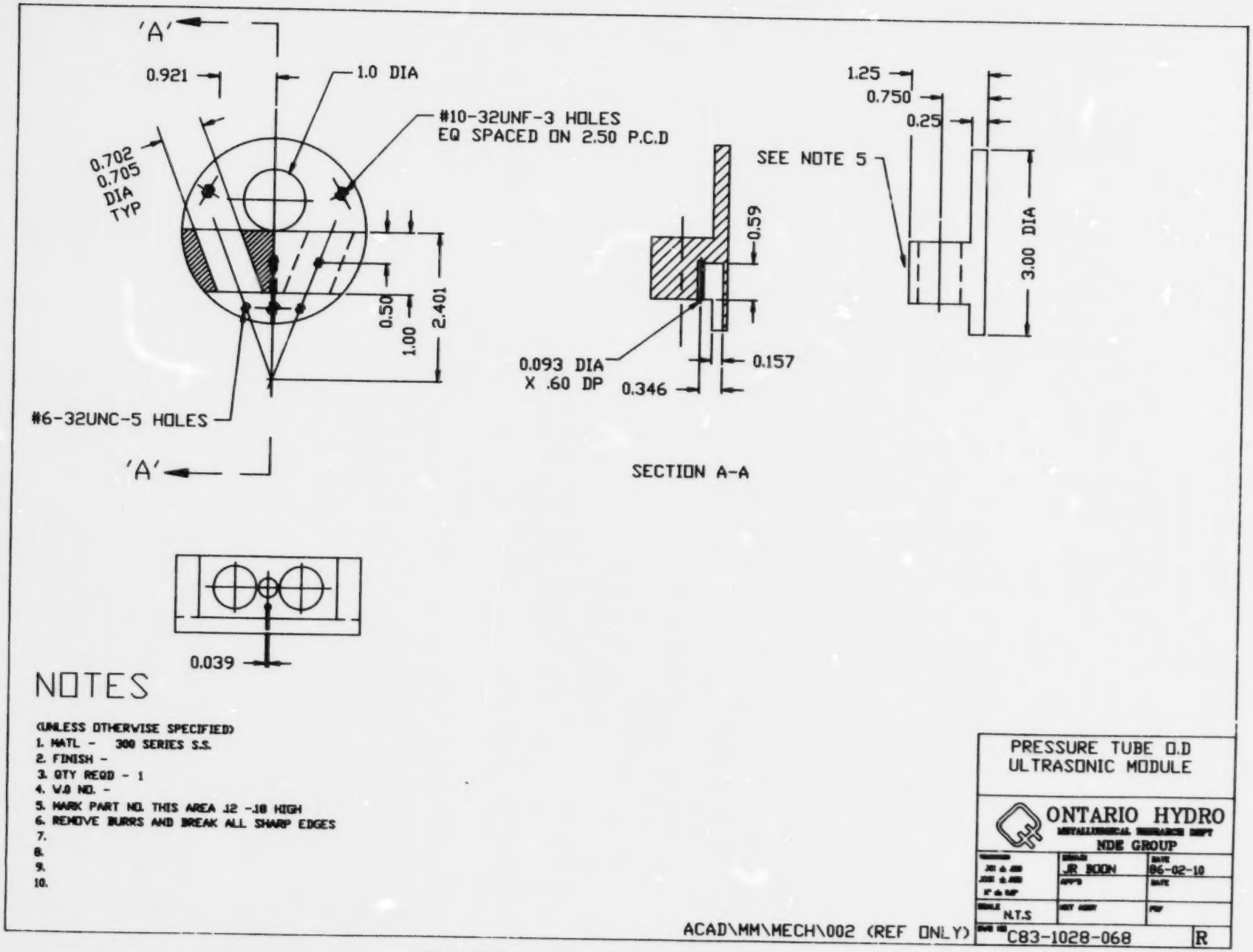


FIG. 3

15 MHz. PROBE. HARISONIC I21502, S/N A10280
PULSE SHAPE AND PULSE SPECTRUM

Note: glass disc reflector
water path 25 mm.



NOTES

(UNLESS OTHERVISE SPECIFIED)

1. MATL - 300 SERIES S.S.
2. FINISH -
3. QTY REQD - 1
4. V.O NO. -
5. MARK PART NO. THIS AREA .12 -.10 HIGH
6. REMOVE BURRS AND BREAK ALL SHARP EDGES
7.
8.
9.
10.

PRESSURE TUBE O.D
ULTRASONIC MODULE

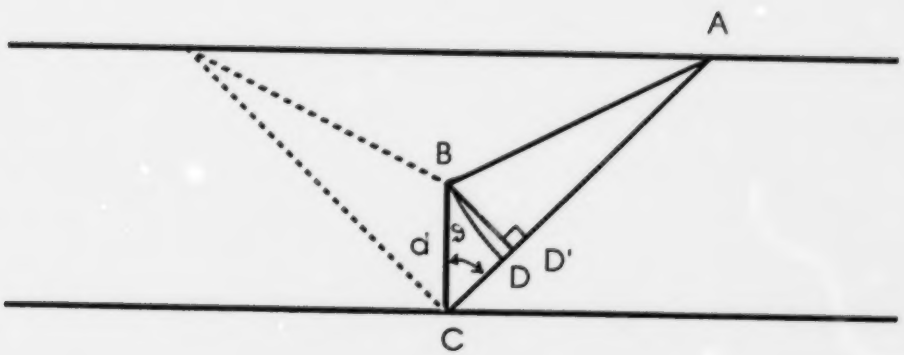
ONTARIO HYDRO
METALLURGICAL INSURANCE DEPT
NDE GROUP

	JR BOON	86-02-10
N.T.S		

ACAD\MM\MECH\002 (REF ONLY)

C83-1028-068 R

FIGURE 4 - DRAWING OF CTD MODULE



$$AC - AB = v\,t / 2$$

$$AB = AD = AD'$$

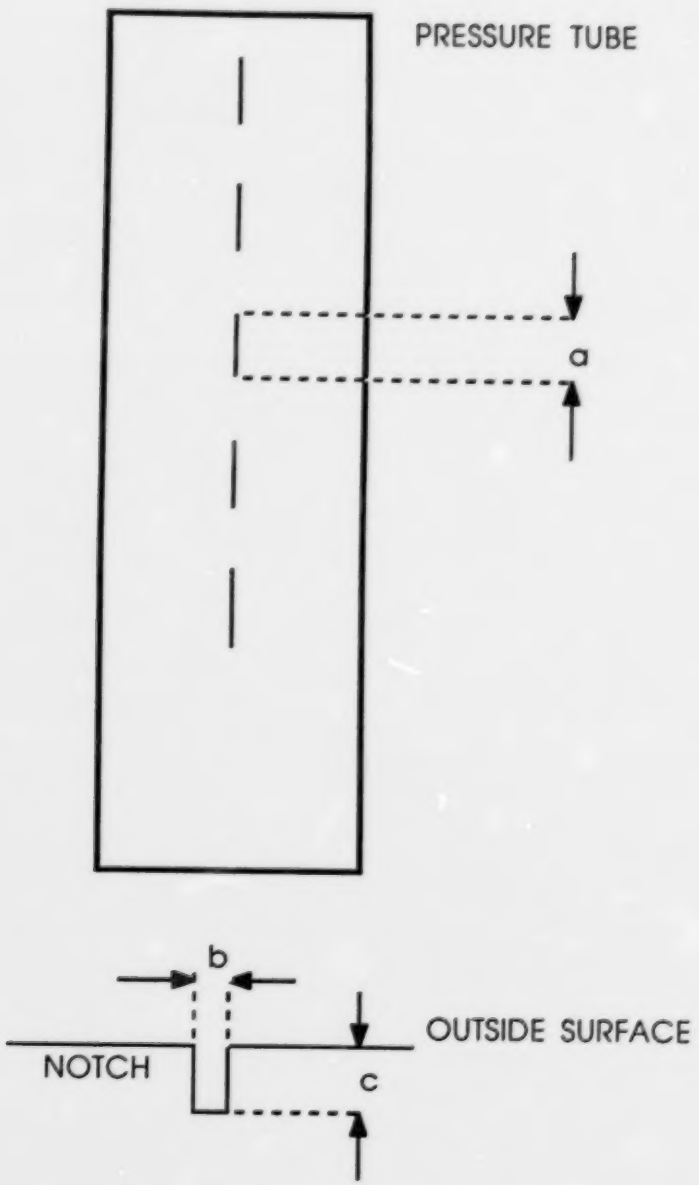
$$AB - AC = CD = CD'$$

$$CD' = d \cos\vartheta$$

$$d = v\,t / 2 \cos\vartheta$$

FIG. 5A

COMPUTATION OF CRACK DEPTH



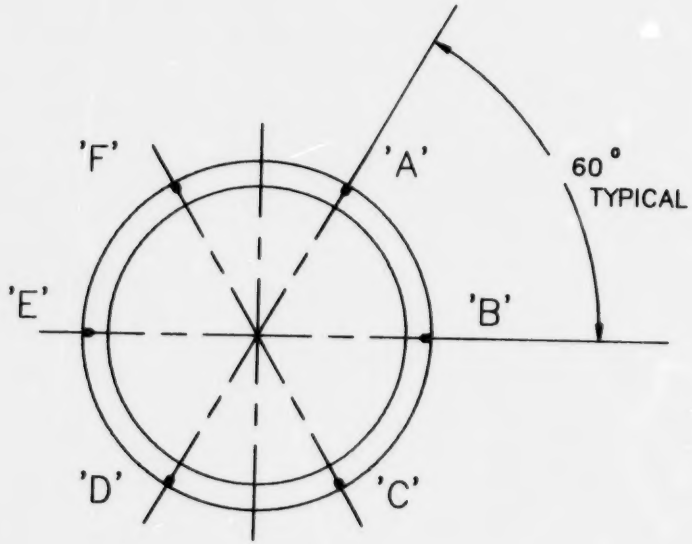
a : notch length 6 mm. (typical)

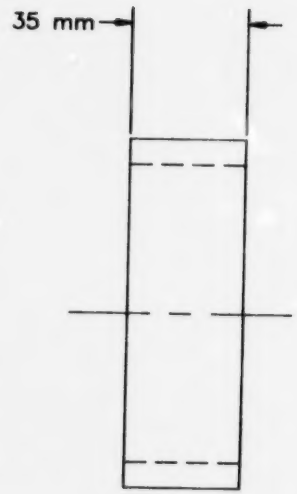
b : notch width 0.15 mm. (typical)

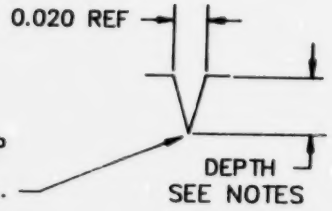
c : notch depth see table 2

NOTE ; notches are parallel to the pressure tube axis

FIG. 5B
THE EDM NOTCHES







DETAIL 'A'

NOTES

1. MATL–ZIRC PRESS TUBE (SUPPLIED)
2. DEPTH OF SLOTS AS FOLLOWS–
   'A'=.006 'D'=.050
   'B'=.010 'E'=.080
   'C'=.025 'F'=.100
   ALL SLOTS TO BE .020 WIDTH
3. FOR SLOT OUTLINE SEE DETAIL 'A'
4. ALL SLOTS TO RUN FULL LENGTH OF TUBE

NOTCHED TUBE

ONTARIO HYDRO
METALLURGICAL RESEARCH DEPT
NDE GROUP

	JR BOON	86-01-10
N.T.S	XXX	83-503
ACAD\MM\MECH\001		R

FIGURE 6 - PRESSURE TUBE SECTION CONTAINING NOTCHES

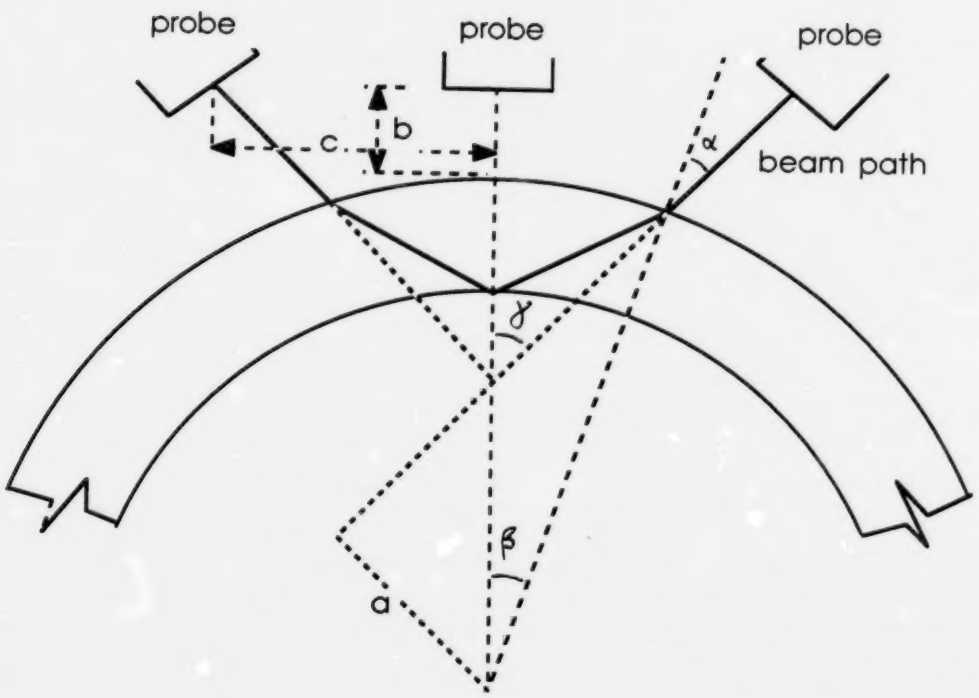


FIG. 7

HUBERT'S CRACK MEASUREMENT: PROBES GEOMETRY

a = 24.2 mm.

b = 30 mm.

c = 20.5 mm.

α = 26.6°

β = 4.3°

γ = 29.9°

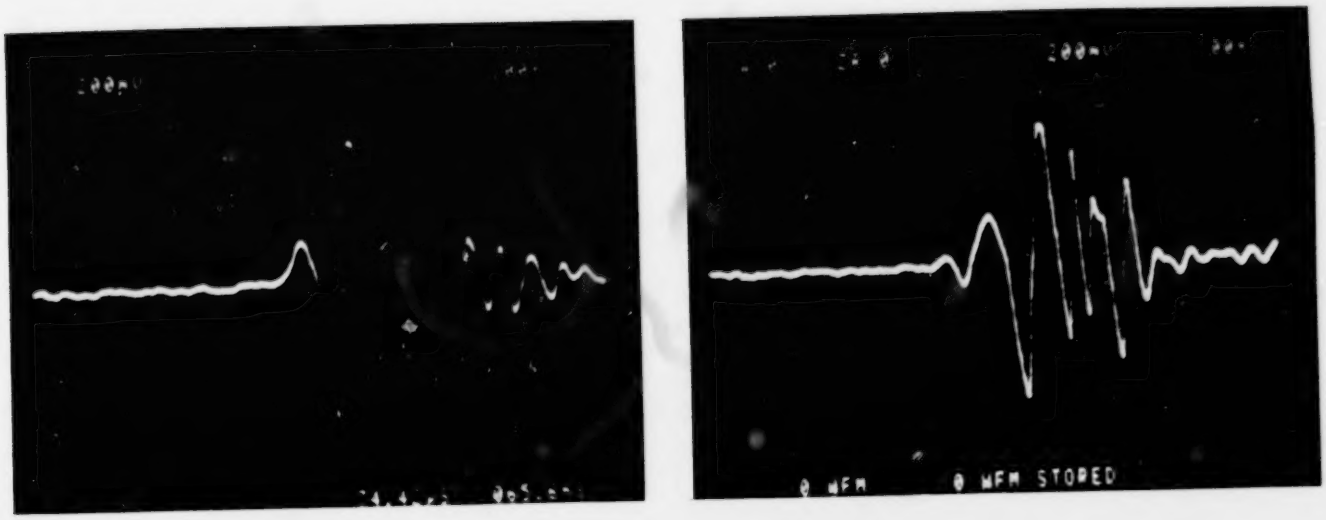


FIG. 8

0.1524 mm. EDM NOTCH

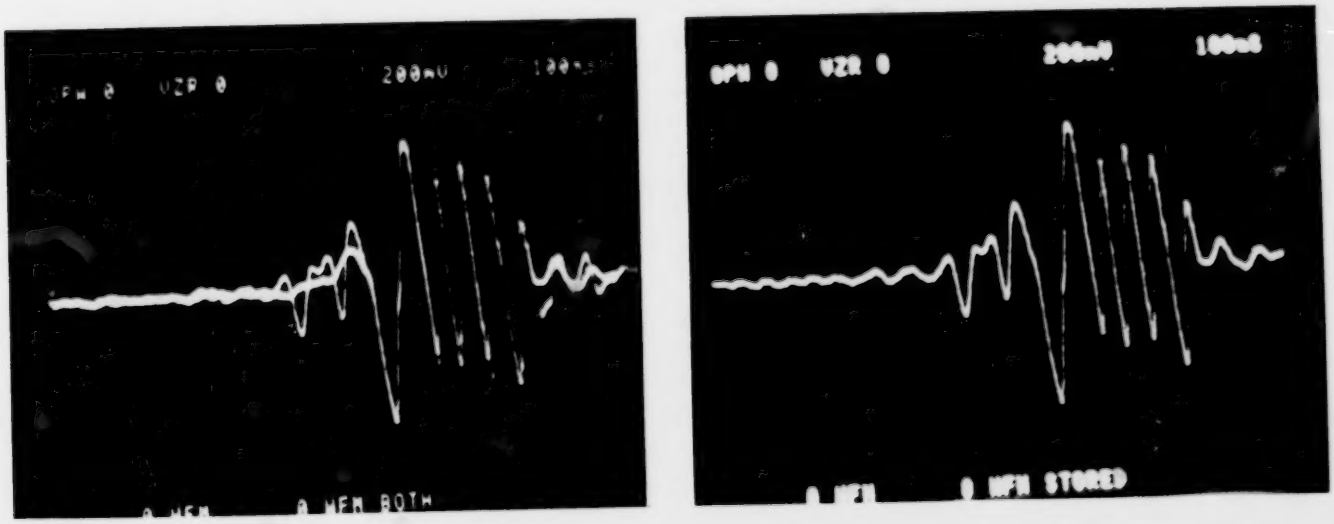


FIG. 9

0.254 mm. EDM NOTCH

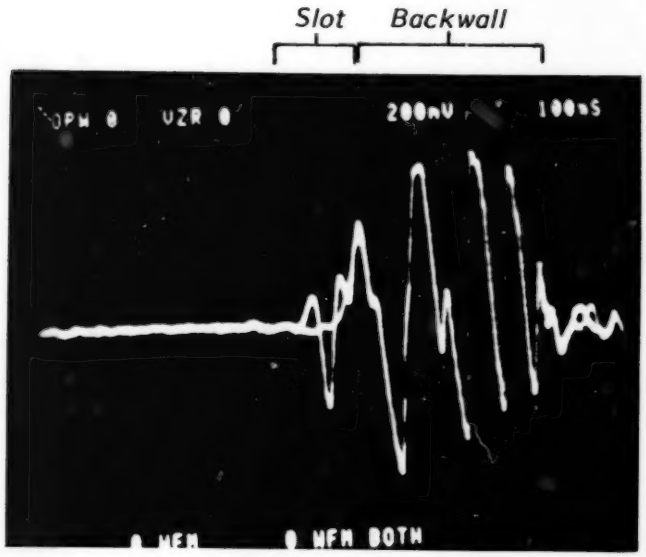


FIG. 10

0.1524 mm. SLOT

Note: the picture shows two signals laid one upon the other; the brighter one is the signal from the slot, the other is the signal from the back-wall, in a area of the tube without any slot

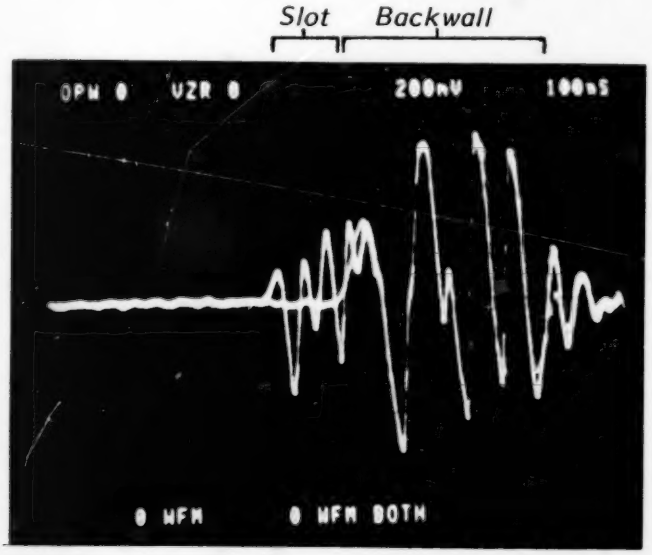


FIG. 11

0.254 mm. SLOT

Note: the picture shows two signals laid one upon the other; the brighter one is the signal from the slot, the other is the signal from the back-wall, in a area of the tube without any slot

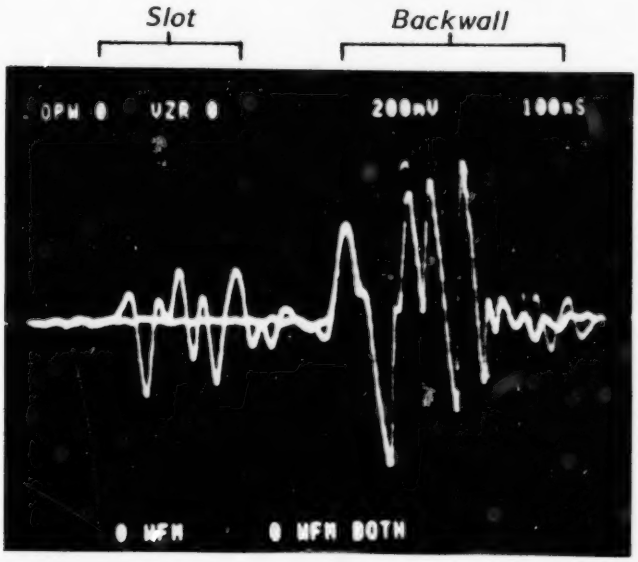


FIG. 12

0.635 mm. SLOT

Note: the picture shows two signals laid one upon the other; the brighter one is the signal from the slot, the other is the signal from the back-wall in a area of the tube without any slot

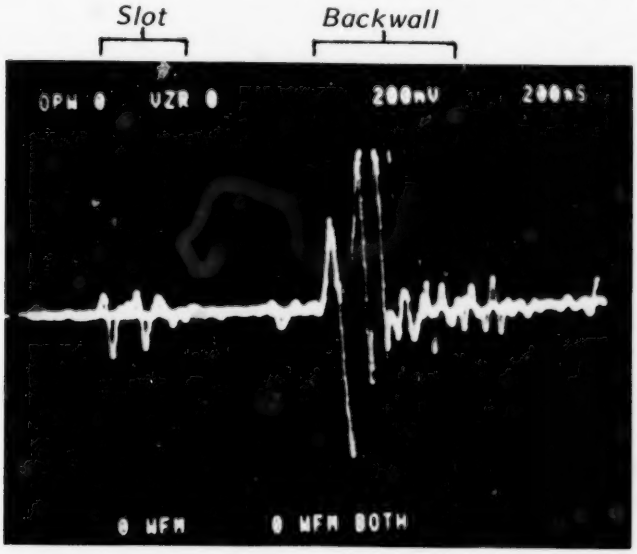


FIG. 13

1.27 mm. SLOT

Note: the picture shows two signals laid one upon the other; the brighter one is the signal from the slot, the other is the signal from the back-wall in a area of the tube without any slot

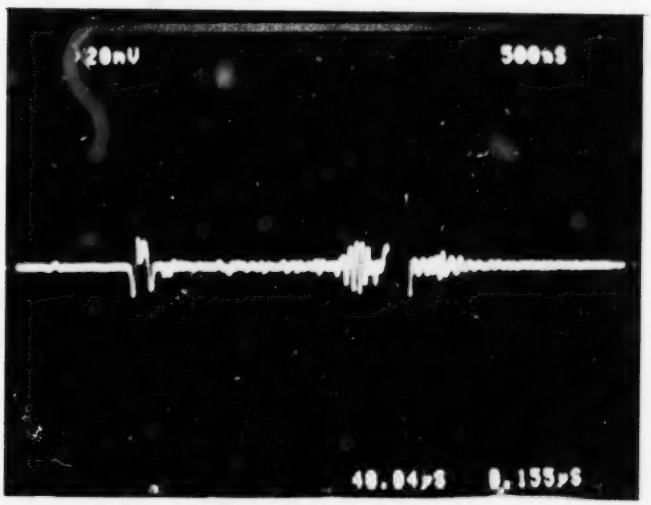


FIG. 14

HUBERT'S CRACK : probes facing crack
SIGNAL FROM THE CRACK TIP

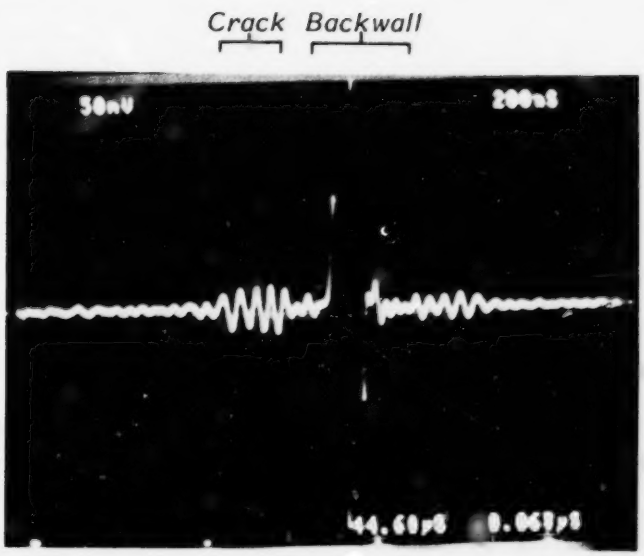


FIG.15

HUBERT'S CRACK : BACKWALL AND CRACK TIP SIGNAL

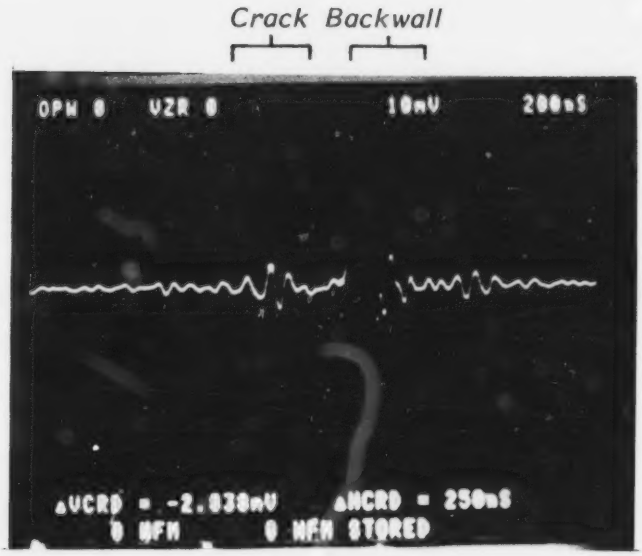


FIG. 16
HUBERT'S CRACK
axial distance from tube bottom 7.5 mm.

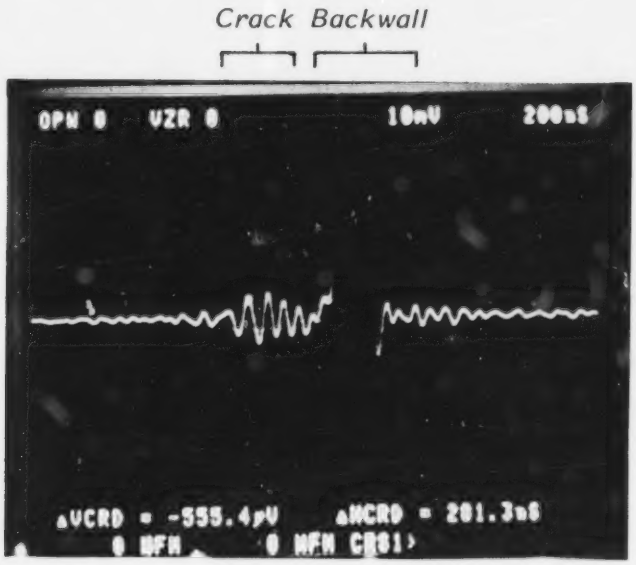


FIG. 17
HUBERT'S CRACK
axial distance from tube bottom 10.5 mm.

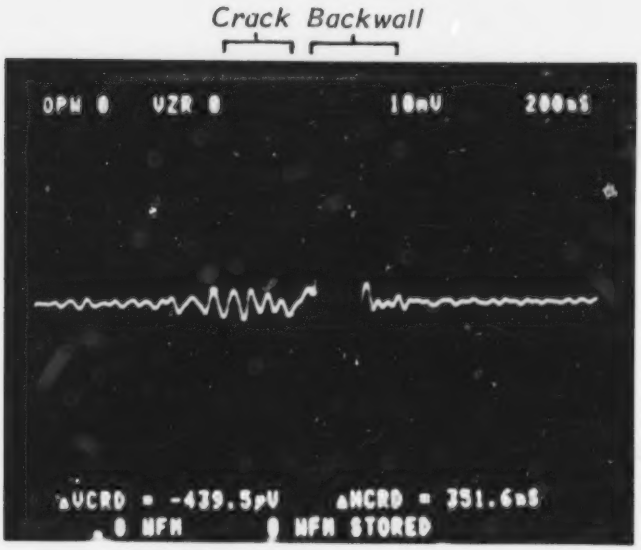


FIG. 18
HUBERT'S CRACK
axial distance from tube bottom 13.5 mm

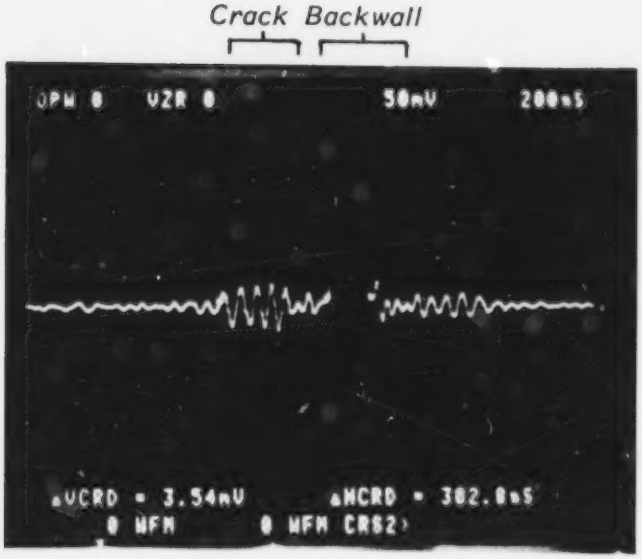


FIG. 19
HUBERT'S CRACK
axial distance from tube bottom 16.5 mm.

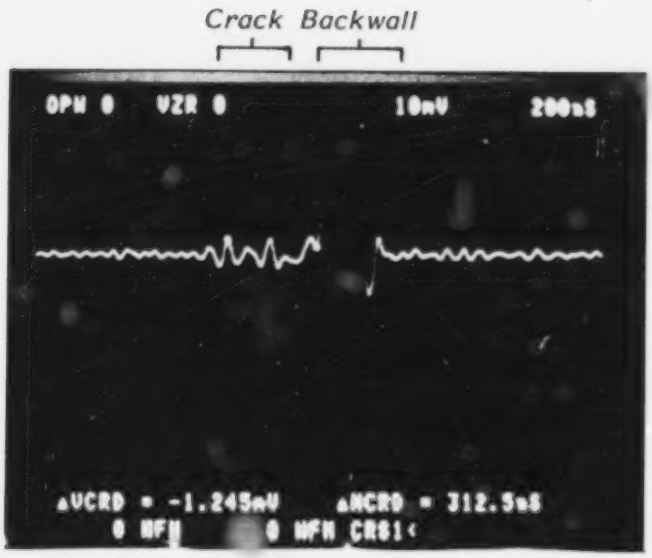


FIG. 20

HUBERT'S CRACK

axial distance from tube bottom 24.5 mm.

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